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Environmental, energy, and economic analysis of integrated treatment of municipal solid waste and sewage sludge: A case study in China

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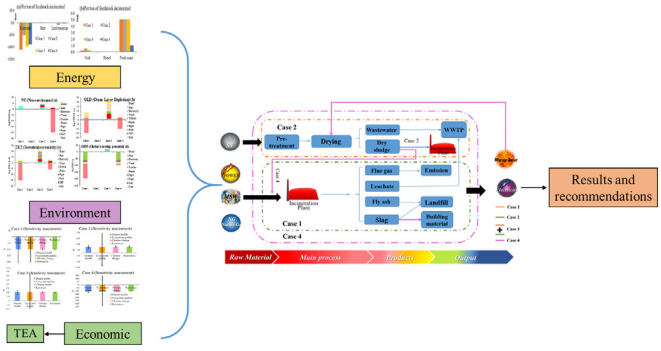
HIGHLIGHTS

- An integrated treatment method of sewage sludge and municipal solid waste was proposed.
- Four scenarios were analyzed in terms of environment, energy and economic impact.
- The integrated treatment had the most positive contribution to climate change and resources.
- The integrated treatment showed best performance of energy efficiency, and significantly saved the non-renewable energy.

GRAPHICAL ABSTRACT



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ABSTRACT

Incineration is well used to treat municipal solid wastes (MSW) but is difficult to treat sewage sludge (SS) because it requires a large amount of heat to remove high content of moisture in SS. Over 50 billion tons of SS are discharged annually in China, and the need for a better waste treatment strategy is urgent. This paper is to introduce a waste disposal technology referring to the integrated treatment of MSW and SS. Four scenarios were analyzed including Mono-incineration of MSW (Case 1) and SS (Case 2), co-incineration of SS and MSW by traditional (Case 3) and integrated ways (Case 4), in terms of environment, energy and economic impact by means of LCA, CED and TEA method. From the environmental perspective, the top four mid-point categories involving the largest effect on four cases are N-C (non-carcinogens), OLD (Ozone layer depletion), TET (Terrestrial eco-toxicity), and GWP (Global warming potential). Case 4 has the most positive effect on climate change and resources (−1.44 kg CO_2 eq and −18 MJ, respectively) according to end-point categories. From the view of energy, Case 4 shows the best performance of energy efficiency, and significantly saves the non-renewable energy (0.21 t coal per ton feedstock compared with Case 3). From the economic part, Case 4 is preferentially potential

Abbreviation: MSW, municipal solid waste; SS, sewage sludge; LCA, life cycle assessment; TEA, techno-economic assessment; CED, cumulative energy demand; WTE, waste-to-energy; WWTP, waste water treatment plant; CFB, circulating fluidized bed; HRSG, heat recovery steam generator; C, carcinogens; NC, non-carcinogens; RI, respiratory inorganics; IR, ionizing radiation; OZD, ozone layer depletion; RO, respiratory organics; AET, aquatic eco-toxicity; TET, terrestrial eco-toxicity; ALO, land occupation; AA, aquatic acidification; AE, aquatic eutrophication; GWP, global warming; NRE, non-renewable energy; ME, mineral extraction.

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with the best profit, cutting down 79.08% of cost in coal than that in Case 3. These results provide understandings of developing an effective approach for co-treating MSW and SS in the near future.

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1. Introduction

With the fast development both in economy and society, China is facing an unprecedented increase in the amount of wastes, over 180 million tons of municipal solid waste (MSW) was generated in 2016 (MSW Pollution Prevention, 2017). Furthermore, it is still increasing at the rate of 8-10% annually (Zhao et al., 2016), accounting for 29% of the world total production (Zhang et al., 2010). Besides, 53.52 billion tons (moisture content: 85%) of sewage sludge (SS) was discharged in 2015. None of other countries has experienced such large quantities and fast growth rate of MSW and SS that China is now facing with (Zheng et al., 2014). So, although MSW/SS treatment is a worldwide issue, it seems more serious in China, up to $1.467 billion's (Zhao et al., 2016) economic losses were owing to the MSW treatment. Taking all these environmental, energy and also economic impacts into account, MSW and SS management have become a national issue so far.

MSW includes both combustible and incombustible fractions such as food waste, paper, textiles, wood, plastics, sand and metal, etc., which hardly bring any value to the first user (Ramachandra et al., 2018). The main MSW treatment methods include landfill, compost, thermal conversion methods (incineration, pyrolysis, gasification), and biological conversion method (anaerobic digestion) (Kumar & Samadder, 2017). Among these technologies, waste-to-energy (WTE) incineration is well accepted as an attractive option, not only dramatically reduce volume of wastes, but also meet the energy demand via generating heat and electricity with the affordable cost (Pavlas et al., 2011). Compared to landfill or compost, without long-term reservation or long-distance transportation, incineration has an enormous advantage. Since the secondary pollution can be efficaciously controlled to a quite low level, the incineration has been continuously developed and encouraged by the Chinese government (Gu et al., 2017). In 2015, the whole incinerator capacity reached a nationwide amount of 0.19 million tons/d. Additionally, 1.6 GW electricity had been generated in China, which is equivalent to saving 83.125 tons of standard coal (Li, 2010). In line with that, waste management through incineration could play a significant role in the source reduction and reuse.

Sewage sludge is considered as the residue produced by the wastewater treatment plants (Fytili, 2006). Due to its particular origin, SS usually contains numerous pathogenic agents, toxic inorganic substances and microorganism, which are detrimental to environment and human health. However, it contains valuable sources, such as phosphorus, nitrogen, and organic carbon (Biganzoli et al., 2012). Currently, there are four main options of treating SS: landfill, incineration, aerobic composting and anaerobic digestion. Of all these methods, landfill or aerobic composting, may seriously pollute the underground water and soil, posing great threat to the public. Anaerobic digestion contains a relative complex process which requires huge investment, and also has limitations of dealing with toxic inorganic substances and microorganism. As a consequence, both mono-incineration and co-incineration technologies have been developed sharply. Although free moisture was largely removed by WWTP, SS still has a relatively high content of moisture, approximately 80 wt. %. Apparently, the components of moisture and inert waste reduce the calorific value of SS to a large extent, and influence its combustibility. Considering massive SS remain to be disposed annually, a comprehensive approach involving energy, environmental and economic views is badly needed.

Incineration technology enables large quantities of SS to achieve reduction, and turns it into energy resources validly. But to reduce the impact on high moisture content of SS, incineration faces both technically and economically difficulties. Therefore, adding SS to MSW may be an interesting integrated treatment for large-scale application considering SS and MSW are produced in city concurrently.

Life cycle assessment (LCA) has been used extensively in last decade to evaluate the environmental benefits and drawbacks of waste to energy technologies (Rousseaux & Suh, 2001). Many researchers estimated the MSW or SS incineration through LCA (Xu et al., 2014; Abuşoğlu et al., 2017; Dong et al., 2018; Lombardelli et al., 2017). For example, in term of SS, Xu et al. (Xu et al., 2014) compared landfill, incineration and anaerobic digestion of SS. Their result shows incineration is the lowest environmental burdens. Abusoglu et al. (Abuşoğlu et al., 2017) analyzed the digested SS incinerator, and found that fluidized bed has a better environmental performance, while cement kiln needs more recovered energy to dry the SS. As for MSW, Dong et al. (Dong et al., 2018) compared pyrolysis, gasification and incineration of MSW, and suggested that modern incineration is superior due to its effective flue gas cleaning system. Giorgia and Raffaele (Lombardelli et al., 2017) used LCA to compare the two waste treatment methods of incineration and landfill, and found that MSW incineration can get more energy surplus. These studies only analysis of SS disposal and MSW disposal methods separately. Up to now, though growing researchers pay attentions to co-utilizations of wastes, further investigate regarding the assessment on co-incineration of MSW and SS is lacking. Beyond that, previous researchers are limited to the environmental impacts, few consider all quantitatively environmental, economic and energy impacts of co-incineration of MSW and SS. Recently, a new built project in Shandong Province applied co-incineration technology of MSW and SS. This project provides a real case for assessing environmental, economic and energy impacts of co-incineration of MSW and SS.

In this work, LCA, techno-economic analysis (TEA) and cumulative energy demand (CED) are used to evaluate the environmental, economic and energy flow burdens associated with the whole life-cycle treatment of a product, process, or activity. And the purpose is to conduct a case study among mono-incineration of MSW (Case 1), mono-incineration of SS (Case 2), superimposed MSW and SS incineration (Case 3), and integrated incineration of MSW and SS (Case 4) ways. Then the four cases were compared quantitatively to analyze their environmental, economic, and energy impacts. This study is interestingly valuable for developing an effective assessment for co-treating MSW and SS in China.

2. Case study descriptions

Four scenarios were selected as Case 1 (mono-incineration MSW), Case 2 (mono-incineration SS), Case 3 (superimposed MSW and SS incineration) and Case 4 (integrated incineration of MSW and SS system) to evaluate its advantages and disadvantages. Three (1, 2 and 4) of these systems were based on the really operating projects, Case 3 is an assumed project. The main technological process flow was shown in Fig. 1.

Case 1. MSW was sent to the incineration plant, which ran a Circulating fluidized bed (CFB) MSW incinerator with the capacity of 1200 t/d.

Case 2. SS was dried to a moisture content of 40%, and then sent to the incineration plant, which ran a Circulating fluidized bed (CFB) MSW incinerator with the capacity of 300 t/d.

Case 3. It was mainly a linear combination of MSW and SS incineration, this case could be seen as two plants being built simultaneously to treat MSW and SS separately.

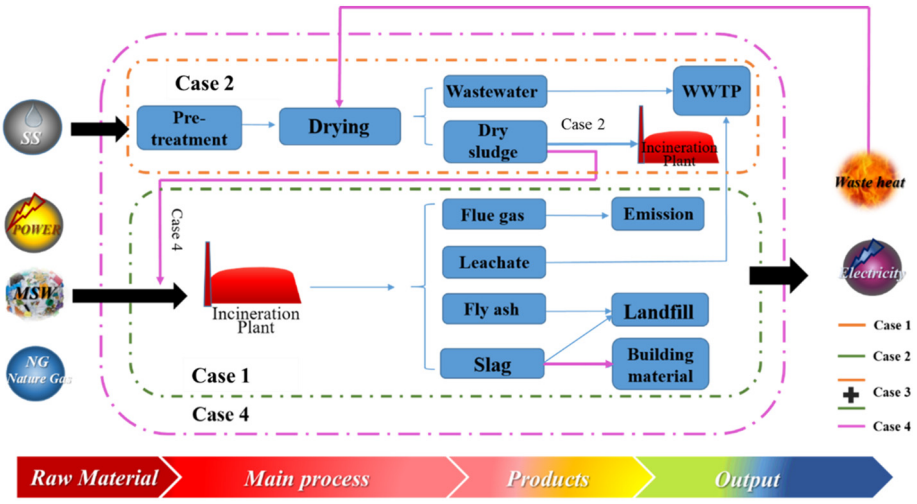

Fig. 1. Main process flow of four cases in this study.

Case 4. Case 4 gave a new integrated treatment of MSW and SS, which could deal with 1200 t of MSW and 300 t of SS in the same incinerator per day.

These four cases were located in Linyi, Shandong Province, an eastern coastal city in China. Case 1, Case 2 and Case 4 are with the same type of incinerator, a circulating fluidized bed. The capacity of the three cases are different, which Case 1 was two 400 t/d and a 700 t/d, Case 2 was 300 t/d, and Case 4 was two 750 t/d. Case 1 was been built in 2008, due to long operating period and low efficiency, the current capacity of three incineration system could only reach 1200 t/d in total. Case 4 was a new built incinerator and it could treat 1200 t/d of MSW and 300 t/d of SS. Details of MSW and SS incinerator were shown in Table 1.

2.1. Case 1: mono-incineration of MSW

To a great extent, MSW is affected by the seasons and rainfall, causing a large range of heat values. Regional difference also results in a quite different ratio of the components. Considering the project was deployed at Shandong Province, MSW from Shandong which mainly contains food waste, paper, textiles, wood, plastics, sand and metal was used, and its ratio of the blends was shown in Table 2. The contents and ratio of MSW in Case 3 and Case 4 were the same as Case 1.

In Case 1 the incineration plant was running based on a Circulating fluidized bed (CFB) MSW incinerator with capacity of 1200 t/d. Considering the LHV of MSW was relatively low, auxiliary fuel (coal) was added to maintain the stability of the incineration process. The amount of the auxiliary fuel was less than 20% of the total fuel weight according to the related regulations. Thanks to the automatic control system and manual operation, the steam parameters of the CFB incinerator could be basically maintained with a stable level.

Fig. 2 shows the main technological process of the MSW incineration power plant in Case 1. It mainly consisted of five systems; combustion system, heat exchange system, flue gas treatment system, and power generation system. After transported MSW was pretreated to reduce the particle size and remove most non-combustible components (metal). The moisture and combustible parts of MSW were directly converted to flue gas through the incinerating unit. While, the non-combustible components (building materials) were collected ad bottom slag or fly ash.

The ignition device was burned with diesel, and generally worked once a month. Primary air and secondary air system were set in this incineration system, and were preheated respectively. In the ignition period, hot flue gas was generated, and fluttered down to the lower part of the chamber. During operating mode, the hot flue gas fluttered directly to the fluidized bed furnace. After incineration, flue gas from super heater, economizer and air preheater, were all gathered to the flue gas cleaning system and bag filter. Before gas emission, this process also required calcium oxide (CaO) to neutralize the acid gases, such as SO_2, HCl, etc. The incineration plant was also equipped with sewage tank, where leachate could be stored temporarily. The detailed consumption of diesel, coal, electricity, etc. in this case was presented in Table 3.

2.2. Case 2: mono-incineration of SS

Sewage sludge has high content of moisture, which exceeds to 80 wt % after a primary drying from the WWTP. To dry the SS usually costs more heat than it can provide, this leads the incineration of SS to a great challenge so far. It certainly will be easier to burn up SS under a moisture content of 10 wt%, however, it requires considerable heat source and the heating system will inevitably become very complicated. As generally recognized (Syed-Hassan et al., 2017), when SS was dried to 40%, it behaves almost the same as the 10% ones, and the economic and environmental cost will become relatively lower. Case 2 dealt with the wet SS with 85 wt% moisture, and this mono-incineration system had a capacity of 300 t/d. SS was dried naturally in a huge channel, chemical reagents were mixed with SS and stirred. SS was then

Table 1
Information about Linyi incineration plant.

Case	Year	CFB		HRSG	Turbo generator	
Case 1	2007	1# Incinerator: 400 t/d × 2	UG-75/5.3-MT-400	75 t/d × 2	24 MW	C25-4.90/0.981
		2# Incinerator: 700 t/d	TG-35/5.3-LJ-700	35 t/d	12 MW	
		Current actual capacity 1200 t/d		Current actual capacity 45 × 2 + 35 = 125 t/d		C12-4.90/0.981
Case 2	2015	3# Incinerator: 300 t/d	NG-65/5.3-W-300	40 t/d	12 MW	C12-4.90/0.981
Case 4	2017	4# Incinerator: 750 t/d × 2	UG-81/5.3-W-750	70 t/d × 2	30 MW	C30-4.9/0.981

Table 2
Components of original MSW on as received basis (wt%).

Components	Combustible					Noncombustible	Low heating value (kJ/kg)
	Food waste	Paper	Plastic (Rubber)	Textiles	Wood	Sand	
Mass ratio (wt. %)	50.8	8.11	11.2	3.20	1.21	25.48	6308

transferred into the crusher, where moisture could be further removed through mechanical process. SS with 40 wt% moisture content was sent to the furnace, while the rest waste water was collected to WWTP.

In Case 2, main flowchart is shown in Fig. 3. CFB incinerator was chosen, and the main difference from Case 1 was the feeding system. Because of the presence of much higher moisture, the feeding system was designed to achieve extremely high quality and stably. More auxiliary fuel was added to avoid extinguishing the fluid bed, approximately 34% of the total fuel weight.

2.3. Case 3: superimposed MSW and SS incineration

Case 3 was a linear combination of MSW and SS incineration. Its main process was the superposition of Case 1 and Case 2. MSW and SS were treated separately in two plants. This case was assumed to compare the pros and cons of separately treating MSW and SS. And especially when government making decisions, Case 3 could be a reference for setting up two independent incineration plant to dispose MSW and SS.

2.4. Case 4: integrated treatment of MSW and SS system

Case 4 gave a new integrated treatment of municipal solid waste and sewage sludge, which could deal with 1200 t of MSW and 300 t of SS with only one incinerator per day. Its difference from Case 4 was that SS and MSW were treated in the same incinerator. Under these circumstances, SS and MSW might have some synergetic reactions during incineration process, and benefit the environment. Apart from that, Case 4 recycled the waste heat of the incinerator to dry the SS, which reduced the additional fuel such as coal or diesel in Cases 2 and 3. Furthermore, fly ash was solidified and sent to sanitary landfill, and leachate was transported to WWTP, while the bottom slag was made into building materials. Other procedures in the incinerator and incineration conditions were same as Case 1.

3. Methods

Fig. 4 shows the flowchart of the system analysis methodology in this study. Firstly, a LCA study was performed to evaluate the potential environmental impacts and resources utilization throughout the incineration power plant. Then, the energy analysis was made among these four cases using CED method. Finally, the TEA was utilized to assess the economic performance by the costs of these treatments.

3.1. Methodology for environmental analysis

LCA has proven to be a useful tool to quantify the environmental impacts of energy and resource consumption caused by waste management technologies over their lifetimes (from cradle-to-grave, cradle-to-cradle, cradle-to-gate, gate-to-gate) (Lin et al., 2016). LCA is composed of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. LCA is capable of assessing from raw material acquisition to products manufacturing, to utilization, end-of-life treatment, and final disposal. In this study, Simapro 8.4 software was used to conduct a gate-to-gate LCA study. ISO 14040 (Principles and Framework) and 14044 (Requirements and Guidelines) were the leading standards for methodological framework in Simapro. Default Swedish EPD (Environmental product declarations) was selected as the impact assessment method in SimaPro. The methodology comprised four steps: functional unit and system boundary definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. The specific contents of each step are detailed below.

3.1.1. Functional unit and system boundary

The goal of this LCA study is to (1) identify the flow(s) or steps that are most 'responsible' for the environmental impacts in the technology and resource recovery; (2) confirm the environmental benefits of the process compared to other cases. In terms of product LCA, the functional unit is usually defined as the output of the system, for example a product (the heat produced in this system). While in a LCA of waste diposal, the functional unit is selected as the input of the system, for example the total waste of a defined geographical region within a given time. In this paper, the functional unit was selected as the environmental impacts of disposing 1 ton of MSW or SS. All consumption, production and emissions of the four cases were given in Table 3. The system boundary started from pre-treatment and ended at the output of useful products resulting from MSW/SS treatment. In order to better understand the

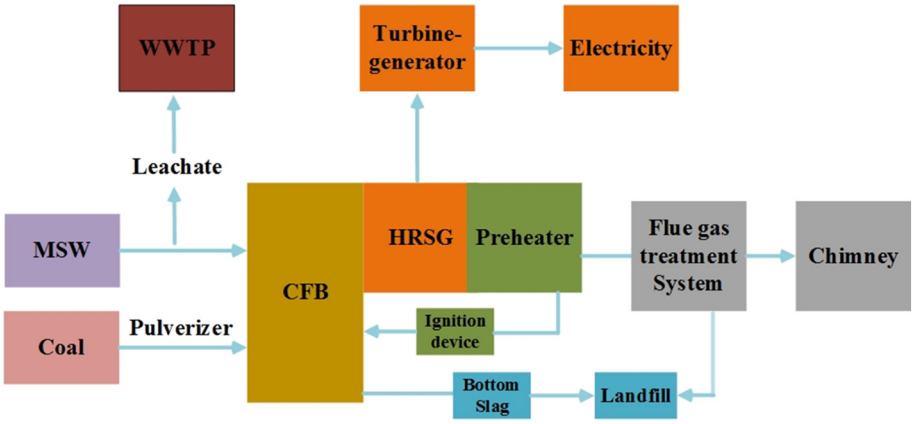

Fig. 2. Main technological process of MSW incineration power plant in Case 1.

Table 3
Life cycle inventories of MSW treatment process.

Item	Unit	Case 1	Case 2	Case 3	Case 4
Energy input					
Electricity	kWh	−1.12E+02	−5.30E+01	−9.84E+01	−9.03E+01
Heat	MJ	−2.07E+03	4.62E+02	−1.61E+03	−1.81E+03
Coal	ton	1.88E−01	5.13E−01	2.63E−01	5.50E−02
Diesel	kg	6.75E−02	5.50E−02	6.46E−02	0.00E+00
Raw materials-fuel					
MSW	ton	1.00E+00	0.00E+00	7.69E−01	7.69E−01
Sewage sludge	ton	0.00E+00	1.00E+00	2.31E−01	2.31E−01
Raw material-chemicals					
Fresh water	ton	5.01E+00	5.01E+00	5.01E+00	1.02E+00
CaO	kg	7.5E+00	6E+00	7.15E+00	7E+00
Direct flue gas emissions					
CO	kg	2.43E−01	1.47E+00	5.25E−01	3.00E−01
CO_2	kg	5.85E+02	5.45E+01	4.50E+02	2.62E+02
SO_2	kg	8.33E−01	1.50E−01	6.75E−01	5.40E−02
NOx	kg	4.86E−01	8.80E−01	5.77E−01	3.60E−01
HCl	kg	8.75E−03	8.90E−03	8.78E−03	1.40E−02
Hg	kg	5.80E−08	4.70E−08	5.55E−08	6.00E−08
As	kg	6.30E−05	8.08E−04	2.35E−04	1.30E−05
Pb	kg	8.28E−05	3.48E−05	7.17E−05	1.35E−05
Cr	kg	4.50E−05	2.27E−04	8.69E−05	8.40E−06
Ni	kg	9.60E−07	2.96E−05	7.58E−06	6.00E−06
PCDD/DFs	kg	8.25E−10	9.75E−10	8.60E−10	2.13E−09
Direct solid emissions					
Fly ash	kg	1.53E+02	1.30E+02	1.48E+02	1.09E+02
Slag	kg	1.53E+02	7.50E+01	1.35E+02	9.40E+01
Direct liquid emissions					
Leachate	kg	4.50E+01	6.00E+01	4.85E+01	1.12E+02

Note: All values are presented per functional unit.

potential environmental benefits (avoided burdens) of the treatment process, assuming that the waste management systems invariably have more than one function (e.g. disposal service and production of energy or secondary materials).

3.1.2. Life cycle inventory and main assumptions

The primary data regarding the waste treatment plant was collected from an actual incineration project in Shandong Province, China. The following data were made in the life-cycle inventory analysis:

(1) In Case 4, all heat and power consumed in SS pre-treatment, sludge drying and water circulating were provided by incineration system. While in Cases 1–3, the power supply for various pumps, fans, and flue gas treatment units was calculated by 23% of the generating capacity, according to the data from the targeted incineration plant. These four cases all generated electricity and was sent to the electric power grid.

(2) According to the current status of Chinese incineration plants, the average operation lifetime of all equipment was 20 years. In Cases 1, 3, 4, the average daily treatment capacity of MSW was 1000 ton. And in Cases 2, 3, 4, the average daily treatment capacity of SS was 300 ton. Therefore, the wastage of each capital equipment used in the operational process was not considered in the evaluation system.

(3) The system boundary about fuel from MSW and SS pre-treating. The upstream of MSW/SS (collection, production, transportation) were excluded. The emission during operation processes of all composition in MSW was calculated.

The energy, materials, and emission inventory to treat 1 ton of MSW and SS for four cases are shown in Table 3. The background databases referring to the supply chain of energy and materials were derived from the Ecoinvent 3.1 which was widely used (Masindi et al., 2018; Ioannouttofa et al., 2016; Duan et al., 2009).

3.1.3. Life cycle impacts assessment method (LCIA)

The LCIA method is based on Impact 2002+ which proposes a feasible implementation of a combined mid/damage method. The Impact 2002+ method employ the emission values of Western Europe as reference values. It is a step-by-step process. All operations were done in the Simapro software. From the LCI results, four damage (endpoint) categories – climate change, human health, ecosystem quality and resources – were evaluated by 15 basic midpoint categories (Global Warming, Carcinogens, Non-carcinogens, Respiratory Inorganics, Ionizing Radiation, Ozone Layer Depletion, Respiratory Organics, Aquatic eco-toxicity, Terrestrial eco-toxicity, Land occupation, Aquatic Acidification, Aquatic Eutrophication, Global Warming, Non-renewable energy, Mineral Extraction). Fig. 5 explains the down-up environmental mechanism. It should be noted that the Ozone Layer Depletion can influence both human health and ecosystem quality.

3.1.4. Results interpretation

On the basis of the life-cycle inventory analysis and life-cycle impact assessment, the last step of LCA summarizes the results of life-cycle impact indicators, identifies significant issues, and provides suggestions for improving environmental sustainability of these four cases. Interpretation is the most versatile phase in LCA, and it reflects the identified limitations and the goal of the study. Uncertainties in the processes may affect LCA results and therefore determine the level of reliability of the analyzed system. Finally, a sensitivity analysis is performed to determine the life cycle assessment results, which could give more insightful suggestions based on it (Lombardelli et al., 2017).

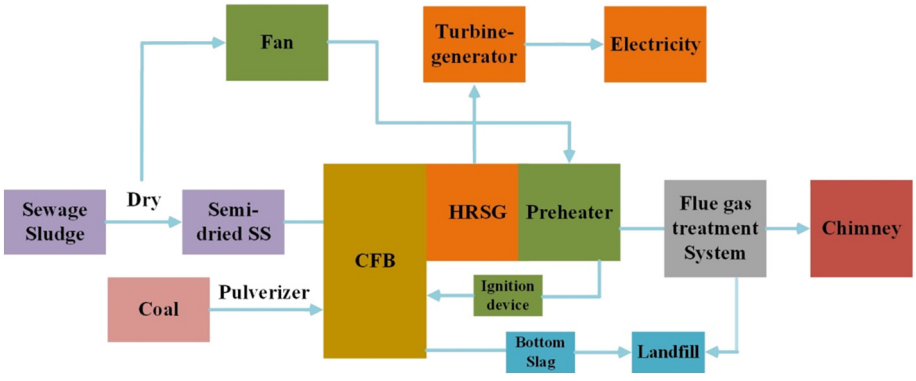

Fig. 3. Main technological process of SS incineration system in Case 2.

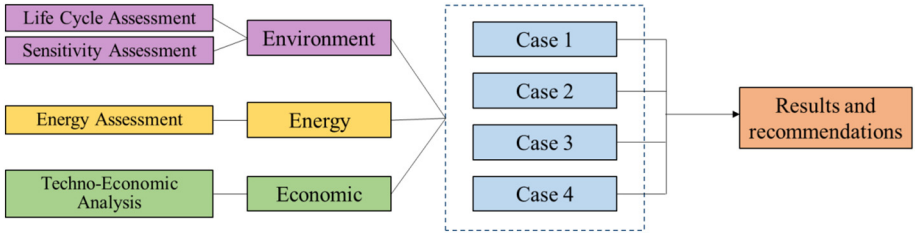

Fig. 4. The flowchart of the system analysis methodology.

3.2. Methodology for energy analysis

In this study, the energy analysis was carried out based on cumulative energy demand (CED) to evaluate the energy use throughout the life cycle about four cases. This included both direct and indirect consumption of energy due to the utilization (Morero et al., 2017). The analysis included the fossil fuel (coal and diesel) demand and the renewable water energy demand. We selected those two items based on the chief constituents of China. Besides, the out of energies were also calculated in these cases.

3.3. Methodology for economic analysis

There were previous studies evaluating the economic and social benefits of incineration plants (Udomsri et al., 2010; McPhail et al., 2013), and the results of these studies show that several parameters are needed to evaluate the monetary. In this paper, more parameters were considered for the above cases, which are divided into three parts: the initial investment, operation cost and revenue. The initial investment includes technology and financial research and development, equipment procurement, installation and commissioning. The operation cost covers daily running expenses, such as chemical reagents cost, administrative cost, transit cost, flue gas treatment cost, etc. The revenue mainly came from the electricity and heat generation, and government subsidies. In addition, the quality of MSW and SS, technology employed and location also have a great impact on the capital cost. Eqs. (1)–(4) were developed to determine the expenditure, revenue and profit of each case.

$$initial\ investment = research + equipment + installation \tag{1}$$

$$expenditures = \Phi\left[\omega_{\#}(\alpha + \zeta + \sigma) + \chi\eta V\theta + \iota_{\#}\upsilon + \tau_{\#}\xi\right] \tag{2}$$

$$revenue = \left(\frac{HV}{B}\right)\mu + \omega_{\#}[\Phi(\gamma + \lambda)] \tag{3}$$

$$profit = revenue - expenditures \tag{4}$$

where Φ stands for operating days/a, ω stands for the mass flow rate of MSW (tons of MSW/d), # represents the numerical identifier of MSW/SS of each case, α stands for the disposal cost of MSW or SS ($/ton of MSW or SS), ζ stands for the cost of transporting the MSW or SS ($/ton of MSW or SS), σstands for the cost of operation and management of the MSW or SS ($/ton of MSW or SS), χ is a coefficient which converts tons to grams (1.10231×10^{-6} tons/g), seconds into days (86,400 s/d), η stands for the conversion for the ideal gas law (g/L) equal to (pressure × molar mass of pollutant) / (R × temperature) with P = 1 atm, R = 0.082 L atm K^{-1} mol^{-1}, and T = 1250 K, V stands for the volumetric flow rate of pollutant (L/s), θ stands for the emission and air permitting fees (¥/Σ(tons of NO_x, SO_2, PM, and volatile organic matter)), ι stands for the mass flow rate of coal (tons/d), υ stands for the coal spot price in China ($/ton of coal), τ stands for the mass flow rate of diesel (kg/d), ξ stands for the diesel spot price in China (¥/ton of coal, 1CNY = 0.1588 USD), HV stands for the heating value (Btu/a), B stands for the heat rate (Btu/MWh), μ stands for the wholesale market price valuation for electricity sales ($/MWh sold), γ stands for the selling price of the building materials ($/ton of recyclable material), and λ represents the municipal revenue for removing the wastes ($/ton of combined recyclables).

4. Results and discussion

4.1. Environmental analysis

4.1.1. Mid-point damage assessments analysis

Table 4 shows the midpoint impacts caused by direct emissions from the four cases considered in this work. Characterization function in Impact 2002+ mid-point life cycle impact assessment results was applied to conduct a comparison among power generation with four cases. According to the common practice in LCA studies, positive value means a

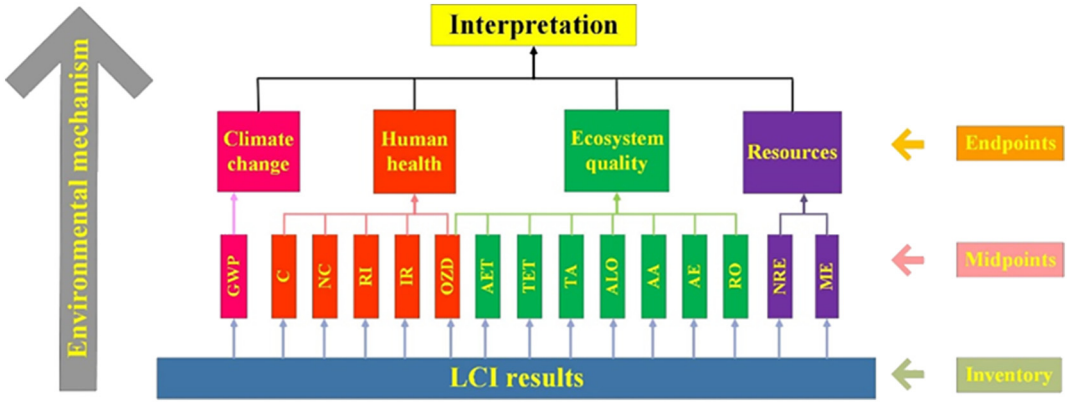

Fig. 5. Overall scheme of the Impact 2002+ framework. Note: GWP, Global Warming; C, Carcinogens; NC, Non-carcinogens; RI, Respiratory Inorganics; IR, Ionizing Radiation; OZD, Ozone Layer Depletion; RO, Respiratory Organics; AET, Aquatic eco-toxicity; TET, Terrestrial eco-toxicity; ALO, Land occupation; AA, Aquatic Acidification; AE, Aquatic Eutrophication; GWP, Global Warming; NRE, Non-renewable energy; ME, Mineral Extraction. (Linking LCI results via midpoint categories to damage categories)

Table 4
Midpoint results caused by direct emissions.

Midpoint categories	Units	Case 1	Case 2	Case 3	Case 4
C	kg C_2H_3Cl eq	−8.07E−04	3.61E−03	2.8E−03	−2.75E−04
N-C	kg C_2H_3Cl eq	−7.55E−04	0.016	0.0152	8.25E-04
RI	kg PM2.5	−5.93E−04	6.27E−04	3.4E−05	−5.17E-04
IR	Bq C-14 eq	−0.556	2.34	1.78	−0.104
OLD	kg CFC-11 eq	−1.87E−09	4.33E−08	4.14E−08	8.71E-09
RO	kg C_2H_4 eq	−1.94E−04	1.96E−04	2E−06	−1.92E−04
AET	kg TEG water	−3.02	24.2	21.2	3.08
TET	kg TEG soil	−0.725	17.2	16.5	3.36
TA/N	kg SO_2 eq	−0.0224	0.0178	−0.0046	−0.0209
LO	M^2 org. arable	−0.0072	0.0167	0.0095	−0.00417
AA	kg SO_2 eq	−0.00379	0.0031	−0.00069	−0.0035
AE	kg PO_4 P-lim	−1.22E−05	4.89E−04	4.77E−04	1.15E−04
GWP	kg CO_2 eq	−0.648	0.865	0.217	−1.44
N-RE	MJ primary	−15.7	17.8	2.1	−18
ME	MJ surplus	−0.00519	0.0187	0.01351	−0.00138

Note: Positive values mean a burden for the environment (thus negative effects), while negative ones represent savings (thus positive effects for the environment).

burden for the environment (thus negative effects), while negative ones represent savings (thus positive effects for the environment).

Case 1 (mono-incineration of MSW) demonstrated less impact for all categories, except for the higher AET impact. Taken every impact category into account, Case 1 has the minimum negative effects compared with other cases, even the maximum positive effects for the environment. Compared with mono-incineration plant of MSW, more heat and coal are needed in mono-incineration of SS. While each impact category of Case 2 (mono-incineration of SS) has a burden to the environment, which means the incineration of SS is still a challenge at present. As for Case 4 (integrated incineration of MSW and SS), though it behaves not well as Case 1, it is still much better than Case 3 (superimposed MSW and SS incineration). That can solve the problem of SS disposal by co-incineration with MSW. As a result, Case 4 is a good choice for SS treatment among four cases, and not too bad for MSW at the same time.

In order to define the most relevant impact categories, the normalization of results is carried out by applying normalization factors (Fig. 6). According to the obtained results, it can be deduced that the top 4 affected categories are N-C (Non-carcinogens), OLD (Ozone Layer Depletion), TET (Terrestrial eco-toxicity) and GWP (Global Warming Potential). These categories are analyzed in following details.

4.1.1.1. NC (Non-carcinogens). The amount of C_2H_3Cl eq is used to measure the effect of N-C. Case 3 had the most negative impact on N-C, (Fig. 7a). The use of CaO caused maximum environmental load in Case 3. The impact of coal takes up the largest proportion in Case 1. Case 4 has the most positive impact on N-C while Case 2 hardly has any impact. Thanks to environmental credits obtained from the heat production, Case 4 has positive impact eventually. The difference between Cases 3 and 4 is also related tightly to the bottom ash and leachate which were directly sent to landfill site in Case 3. As a consequent, emissions of arsenic and antimony were inevitable. In Case 4, bottom slag and other metals were sent to make building materials, which highly cuts down the N-C effect.

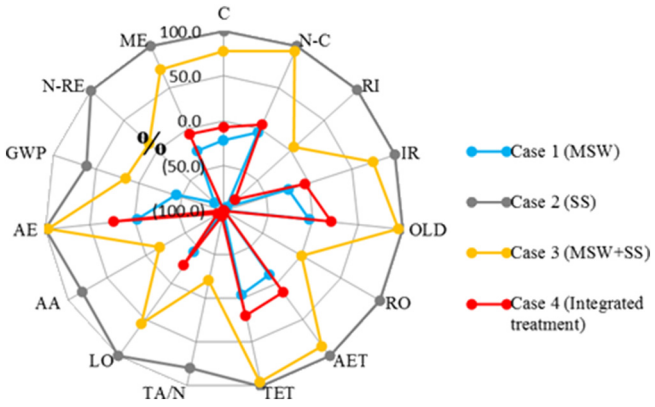

Fig. 6. Normalized impact categories in each case

4.1.1.2. OLD (ozone layer depletion). Kg CFC-11 eq was used to stand for the impact on OLD (Fig. 7b). CFC might indirectly affect the stratospheric 'ozone layer' through their ability to transport halogens, particularly chlorine, to this level (Noakes, 1995). Case 1 and Case 4 both have positive contribution to the OLD. Coal, plastic, CaO and food waste in Case 3 resulted in a relative higher negative impact on OLD. Plastic is the most damaging substance in these cases, which is responsible for the potential to damage the environment. The impact of Case 2 is almost negligible. In total, although Case 1 has the most positive effect on the OLD, Case 4 could certainly seem as a valid and environmentally friendly way to reduce SS and MSW.

4.1.1.3. TET (terrestrial eco-toxicity). From the perspective of TET category, the biggest burden was also originated from Case 3 (Fig. 7c). Among these cases, the main contributors are the leachate emissions into the soil and to the atmosphere caused by diesel and coal consumption. Therefore, the consumption of coal (12%) and diesel (13%) in Case 1, contributes significantly to TET category. While electricity and heat production offset the most negative fraction and the pretreatment of MSW emits 20% of terrestrial eco-toxicity pollutants in Case 4. Production of power allows a significant cutback in terrestrial eco-toxicity substances: 25.8194 kg TEG soil (Case 1), 7.1853 kg TEG soil (Case 4). Case 2 has a relatively low positive impact in TET. Diesel had the greatest influence on TET. For Case 3, diesel, electricity, wood, textiles, plastic, paper, food, CaO and coal all cause a bad influence on TET.

4.1.1.4. GWP (global warming potential). Case 3 presents the highest GWP, mainly due to the coal emissions (17.88 kg CO_2 eq) that generated large emissions of greenhouse gas. In Case 1, the main contributor is the heat production and food disposal (102 kg CO_2 eq and 73 kg CO_2 eq). Case 4 also made a positive contribution to mitigating global warming. Food waste and plastic are two main contributors in this case (63 kg CO_2 eq and 25 kg CO_2 eq, respectively). 199 kg CO_2 eq (Case 1) and 99 kg CO_2 eq (Case 4) of greenhouse gases were avoided by the heat and power production. Similarly, the impact of Case 2 is also almost negligible.

4.1.2. End-point categories assessment analysis

Table 5 lists the direct impact of four cases on each end-point categories (human health, ecosystem quality, climate change and resources). Obviously, Case 1 still has a positive effect on four categories and Case 2 illustrates a fact that mono-incineration of SS is unreasonable. It could cause huge loss on resources. Therefore, the main objective of this study was to examine the environmental effects of co-incineration of MSW and SS. Under this circumstance, weighting was calculated for the impact categories of human health, ecosystem quality, climate change and resources (Fig. 8).

In contrast, the resources and climate change impacts of this pathway are significantly higher. Although Case 4 has the biggest contribution to resources and climate change effects, its impact on ecosystem quality is higher than other three cases (Only Case 4 and Case 3 have negative effect). The environmental performance of Case 2 is poor; Case 1 displays an overall positive effect on four categories. With the exception of the slightly higher ecosystem quality impact, Case 2 has the most negative impact for all categories.

4.1.3. Sensitive analysis of end-point category

Sensitivity analysis was conducted to assess the robustness of the results by modifying relevant operations of the analyzed cases. For

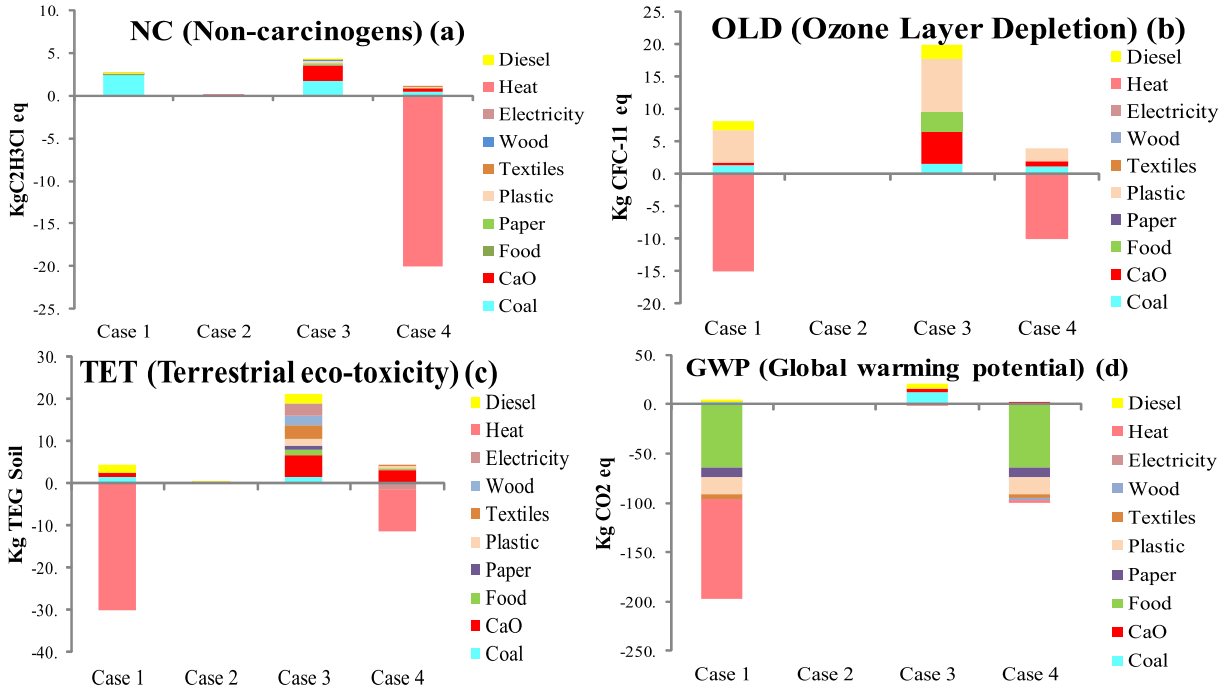

Fig. 7. Process contribution of four cases, analyzed by Impact 2002+.

illustration, Fig. 9 presents the sensitivity analysis result of four end-point damage categories based on changes in electricity use, fuel consumption. The basic data was expressed as 100% and −100% according to its sign symbol.

It could be seen that the uncertainty of ecosystem quality of four cases is the biggest. This may due to lacking the knowledge of ecosystem about the dynamics. These include the processes that allows for ecological functions, how these functions provided valuable ecosystem services, and how these change in response to altered environmental conditions (Bullock & O'Shea, 2016). Besides, the uncertainty of human health indicator in Case 1 is still relatively huge (high 106.98% and low 102.58%). The component of MSW is variable according to people's habits. Other uncertainties are below 25%, which are highly credible. In summary, the results of uncertainty analysis illustrate that the effect on environment of Case 4 was the lowest and best among four cases.

4.2. Energy analysis

The results from CED analysis are shown in Fig. 10. Fig. 10a covers the avoided energy generated by the WtE processes (coal, electricity and land resources, respectively), and Fig. 10b compares the energy demanded of four waste treatment methods.

The available land in China is becoming fewer. In 2015, there was a reduction of cultivated land area by 301,700 ha due to construction occupation, disaster destruction, ecological restoration and agricultural restructuring (Bulletin, 2017). Choosing landfill as a method of treating SS or MSW would aggravate this tendency. As it is shown in Fig. 10a, 1.67 m^3, 10.24 m^3, 3,65 m^3, 3.65 m^3 of land resources are saved separately by these four incineration cases, instead of landfill.

Furthermore, clean energy like electricity, hot water and steam, are generated by MSW and SS incineration, and could be fed into power grid or supply heat to residents or plants nearby. Meanwhile, these clean energies could also meet the demands of other part of the industry park (including drying the raw Sewage Sludge). It is visible that Case 4 produced more than Case 2 does, although it is a little lower than Cases 1 and 3, Case 4 is around same level with them.

Fig. 10b shows that fresh water is the highest energy demand in the incineration process, since it is needed in the flue gas treatment system to dissolve SO_2 and NO_x, and unrecyclable. Besides, the demand of coal is higher than diesel, for that coal is considered as an auxiliary fuel, and joins the main incineration process. But the purpose of using diesel

Table 5
Direct damage of four cases (analyzed using Impact 2002+).

Damage category	Unit	Case 1	Case 2	Case 3	Case 4
Human health	DALY	−4.2E−07	4.95E−07	7.5E−08	−3.61E−07
Ecosystem quality	PDF*M2*yr	−0.037	0.174	0.137	4.88E−04
Climate change	kg CO_2 eq	−0.648	0.865	0.217	−1.44
Resources	MJ	−15.7	17.9	2.2	−18

Note: DALY (Disability Adjusted Life Years) – One DALY can be regarded as one lost year of "healthy" life. The sum of these DALYs across the population, or the burden of disease, can be considered as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability.
PDF*M2*yr (Potentially Decrease Fraction) – It stands for the amount of loss of a species in a particular area, in a given period of time.
MJ – Expressed as use of minerals and fossil fuels for the extraction of additional energy consumption.

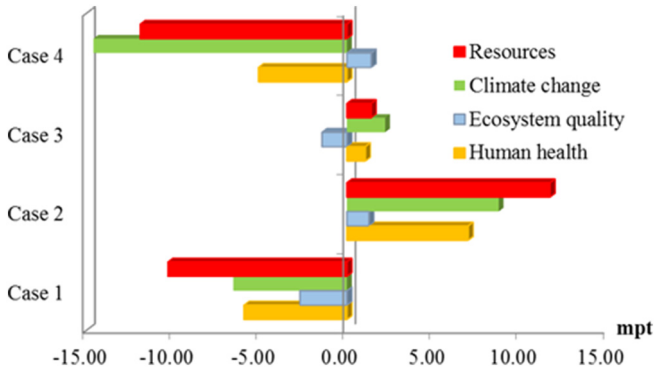

Fig. 8. Normalized comparison of four cases.

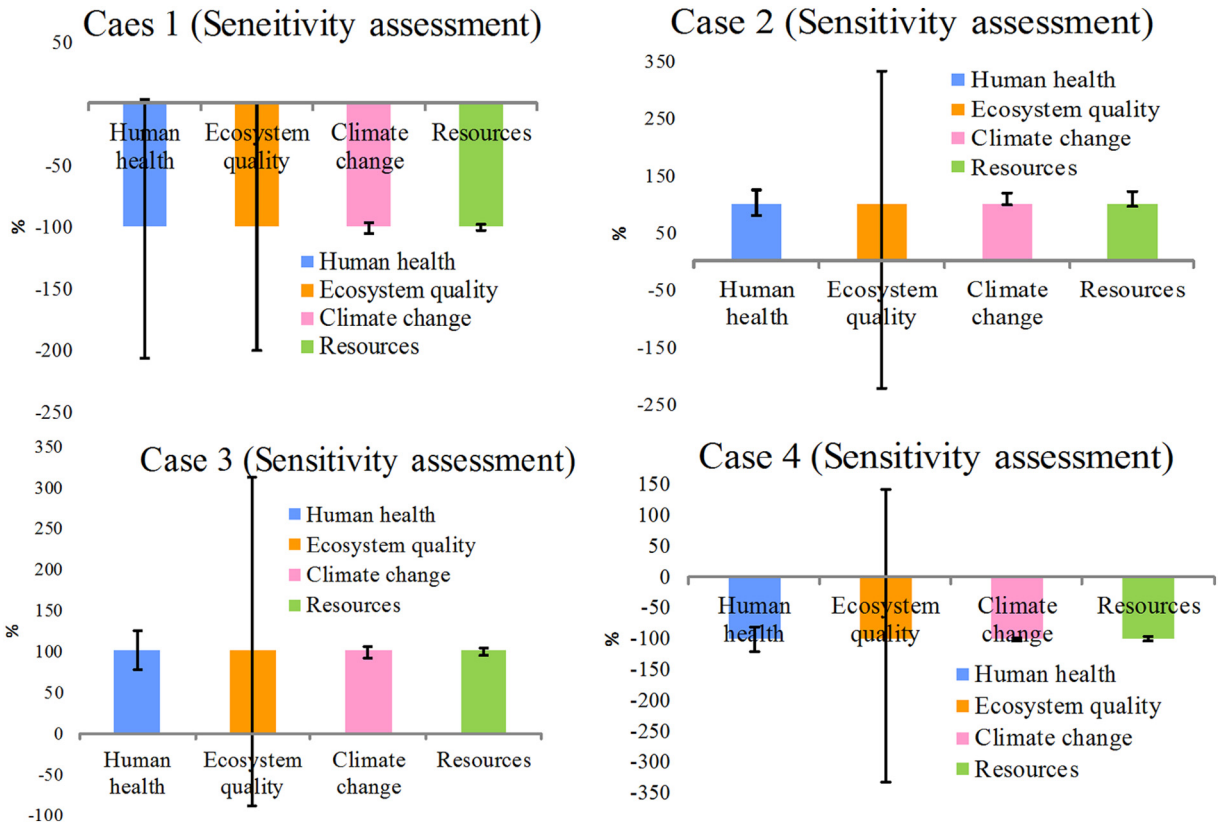

Fig. 9. Sensitivity assessment for four cases (analyzed by Impact 2002+).

was to start the furnace, which happened only once a month. In Case 4, there was an obvious decrement in the usage of coal. It was highly related to the low moisture content of SS, which leads to a better combustion efficiency. Co-incineration process of Case 4 has a significant in saving the non-renewable energy (0.21 t coal per ton feedstock compared to Case 3).

MSW and SS as two main wastes generated from human being were then turned into clean energy, and finally serve the people in daily life. Case 4 supplied large amount of electricity and consume less non-renewable energy at the same time, which was a good method for integrated treating the wastes.

4.3. Economic analysis

The approximate capital cost requirements along with estimates variable costs like chemical reagents, flue gas treatment, operation and maintenance of the incineration plant have been considered. The net electrical/heat power of the plant and related parameters and results derived from Eqs. (1)–(4) is given in Table 6, which is valid for developing countries like China. The actual cost also depends on various other factors for instance, raw material, and governmental incentives (Ouda et al., 2016). In addition, the availability of skilled labor and MSW/SS collecting distance were not taken into account in this study. So the profit is not necessarily representative of what a real WtE plant earns (McPhail et al., 2013). However, the cost for collecting MSW and SS are the same in each case, so it has no influence to the results.

Case 4 shows the biggest profit among four cases, this was mainly because it has the lowest expenditure of coal, 89.74% of total cost in Case 2, and 52.57% in Case 4. The output of power (electricity and heat) is basically the same in Cases 1, 3, 4, while Case 2 is poor. The pre-treatment of SS might counteract the generation of heat, and needs more auxiliary fuel to dry it. If the usage of coal could be reduced, in another word, if there are heat directly input to the SS incinerator like Case 4, Case 2 could become more cost-effective.

The total operation cost is also directly tied to the treatment of fly ash and bottom slag. Bottom slag in Case 4 was sent to make building materials, which not only saves the land resources from landfill, but also gains some profit by selling the building materials. The most bottom slag is coming from incombustible components like metals and sand, so it is with great importance to classify MSW before transported

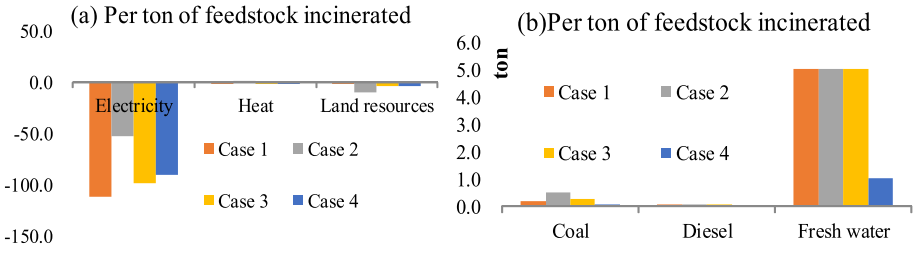

Fig. 10. CED results: (a) included output and avoided energy from the incineration processes and (b) comparison of alternatives.

Table 6
Initial investment, operating costs, revenue and profit (CNY/d).

Items	Case 1	Case 2	Case 3	Case 4
Operating hours	7200 h			
Initial investment				
Capital cost	9.3	12.4	16.67	14.47
Operation cost				
Transit cost	0	0	0	1.038
Operation & maintenance	5.58	7.44	10.01	8.68
Water	15.13	15.13	15.13	3.08
Coal	141.27	385.48	197.62	41.33
Diesel	0.26	0.21	0.25	0
Flue gas treatment (SO_2, NO_x)	7.29	5.70	6.92	2.29
Chemical reagents (CaO)	0.98	0.78	0.93	9.10
Fly ash	10.71	9.1	10.36	7.63
Bottom slag	6.12	3	5.4	0
Leachate	2.025	2.7	2.7	5.04
Revenue				
Electricity price (for MSW)	72.80	34.45	63.70	58.70
Heat price (for MSW)	91.00	0	70.67	79.46
MSW government subsidy	151	0	116	116
SS government subsidy	0	80	18.46	18.46
Industrial material price	0	0	0	3.76
Profit				
Profit	125.44	−315.08	19.51	199.23

Note: Values are presented per functional unit. 1 CNY = 0.1588 USD.

to the incineration plant. Besides, in each case, flue gas (SO_2, NO_x) treatment also contributes a certain amount to the total operation cost, which is 3.85% of the total cost in Case 1, and could be reduced to 2.9% in Case 4. It is speculated that all cycles of these four cases could be economically variable with the usage duration.

Among these four cases, Case 3 has a highest initial investment, which is almost twice as Case 1. This is mainly because two incineration plants should be built to treat SS and MSW separately. Case 4 is the second highest, due to the high cost of technology research. Generally speaking, Case 4 shows best potential in the economic analysis, making it a reasonable integrated treatment of MSW and SS compared to Case 3, and creating the feasibility of SS incineration from the economical part.

From a quantitative perspective, TEA method provides a better understanding of the characteristics associated with body of economic accounting. TEA has a suite of indicators that can be combined to provide a useful picture for the development of integrated treatment of MSW and SS. Moreover, the TEA method adopted in this study provides an innovative tool which could be used in the future studies to analysis positive (negative) topic in MSW research fields.

5. Conclusions

In this work, a multi-criterion environmental, economic and energy analyses of Integrated Treatment of MSW and SS was conducted, focusing on selecting the most appropriate project to realize efficiency maximization:

(1) From the environmental perspective, the top four mid-point categories that had the largest effect on four cases are N-C (Non-carcinogens), OLD (Ozone Layer Depletion), TET (Terrestrial ecotoxicity), and GWP (Global Warming Potential). Case 2 and Case 3 have negative effect to them, while Case 1 and Case 4 have positive contribution to them. As for the end-point categories, Case 4 has the most positive effect on climate change and resources (−1.44 kg CO_2 eq and −18 MJ, respectively). It is better than Case 1 and Case 3, which proved to be the most implementable technology. Besides, the heat and electricity production further promote the energy saving.

(2) From the view of energy, Case 4 supplies large amount of electricity and consume less non-renewable energy at the same time. It saves land resources, again makes full use of the waste heat to remove the moisture in SS. Recycling the bottom slag to make building materials, and also realized the recycling utilization. Besides, Case 4 has an obvious decrement usage of coal, 0.21 t coal per ton feedstock compared with Case 3.

(3) From the economic part, Case 4 shows the best potential. Although it seems a little higher in the initial investment, it displays the best profit among four treatment methods. Because of the lowest expenditure of coal, (89.74% and 52.57% of total cost in Case 2 and Case 4), it is considered as a reasonable integrated treatment of MSW and SS compared with Case 3, and shows the feasibility of SS incineration from the economical part.

This paper provides quantitative information to help understand the LCA method and direction of environmental impacts for MSW and SS disposal technology. The LCA is a comprehensive evaluation and stands at a higher level to make an overall assessment for technologies, rather than focus on a specific step or process. Four environmental indicators such as human health, ecosystem, climate change and resources are used to describe the damage index of the materials or processes. Thus, this research provides a useful reference for waste disposal, academics, waste management researchers, and policy decision makers.

Issue to be addressed in the future research: Result shows that certain synergetic effect existed between the co-incineration process of MSW and SS. Further investigations should focus on exploring the linear and nonlinear laws of the blends.

Acknowledgements

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